

An active asteroid belt causing the UX Ori phenomenon in RZ Psc

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ABSTRACT

We report the discovery of mid-IR excess emission in the young object RZ Psc. The excess constitutes $\sim 8\%$ of its L_{bol} , and is well fit by a single 500 K blackbody implying a dust free region within ~ 0.7 AU, for optically thick dust. The object displays dust obscuration events (UXOR behaviour) with a timescale that suggests dusty material on orbits of ~ 0.5 AU. We also report a 12.4 year cyclical photometric variability which can be interpreted as due to perturbations in the dust distribution. The system is characterized by a high inclination, marginal extinction (during bright photometric states), a single temperature for the warm dust, and an age estimate which puts the star beyond the formation stage. We propose that the dust occultation events present a dynamical view of an active asteroid belt whose collisional products sporadically obscure the central star.

Key words. stars: variables: T Tauri Herbig Ae/Be – stars: individual: RZ Psc – planet-disk interactions – technique: photometric

1. Introduction

In the course of the formation of a star, an equatorial disk is present whose purpose evolves from an angular momentum redistributor facilitating star growth to a planet builder. Dust grains in the disk change chemically (Bouwman et al. 2001) and physically through growth (van Boekel et al. 2004) and collisions (Wyatt et al. 2007b). Observations demonstrate on the one hand the presence of dust disks by their tell-tale thermal infrared spectrum, whereas on the other hand hundreds of mature planetary systems are now known. Yet, how the dust disk evolves to a planetary system is not well understood (Williams & Cieza 2011).

RZ Psc is a solar-type star (K0 IV, Herbig 1960) and well-known for its brightness variability with time. The variability has all the hallmarks of the so-called UXOR variability seen among pre-main sequence stars. They sporadically have photometric minima with amplitudes of $\Delta V \approx 2^m - 3^m$ which last from a few days up to a few weeks. During a minimum, the UXOR displays bluer optical colours and an increased linear polarization due to an increased contribution by scattered light off small dust grains (e.g. Grinin 1988; Grinin et al. 1991). This type of variability is strictly associated with the occultation of the star by dust in the optically thick accretion disks of stars younger than 10 million years (Dullemond et al. 2003). The age of RZ Psc is estimated to be approximately a factor three older (Grinin et al. 2010, hereafter paper I). Correspondingly, the star does not display the benchmark properties of young stars like ionized gas transitions or excess emission by hot (1500 K) dust (Bertout 1989; Paper I). RZ Psc is therefore enigmatic because of a variability normally caused by optically thick accretion disks. In this follow-up study, we report that the object has one of the

strongest infrared excesses observed to date and provide a detailed periodicity analysis of the optical variability.

2. The observational data

In order to shed light on the cause for the star's continuum emission variability, peculiar for its age, we explored the mid-infrared and far-infrared wavelength region by means of data obtained by a variety of infrared satellite missions and ground-based surveys, viz. *Wide-field Infrared Survey Explorer* (WISE, Wright et al. 2010), *Infrared Astronomical Satellite* (IRAS), *AKARI* (Ishihara et al. 2010) and the *Two Micron All Sky Survey* (2MASS, Cutri et al. 2003). We also present new V-band photometry taken at the Crimean Astrophysical Observatory (CrAO) extending the star's light curve to March 2012 (see Fig. 2).

Representative *UBVRI* magnitudes for the star's photosphere are taken from the mean value of the three brightest measurements, assuming that these are least affected by circumstellar extinction. The 2MASS near-IR magnitudes in the *JHK* bands reveal no change with respect to the measurements by Glass & Penston (1974), $H = 9.7 \pm 0.2$ and $K = 9.78 \pm 0.1$. The WISE point source coincides with RZ Psc within $0.3''$ and is the only catalogued WISE source within a $23''$ radius of our target. We also note that the IRAS $12\mu\text{m}$ flux is consistent with the WISE flux measurement at $11.6\mu\text{m}$. Finally, the IRAS Faint Source Reject Catalog contains flux upper limits at $60\mu\text{m}$ and $100\mu\text{m}$.

3. Results and discussion

In paper I, we estimated an age for RZ Psc of 30–40 Myr based on its kinematics and Lithium absorption. An age constraint using the star's space motion was performed, exploiting the high galactic latitude of $b \sim 35^\circ$, and assuming that the star formed at

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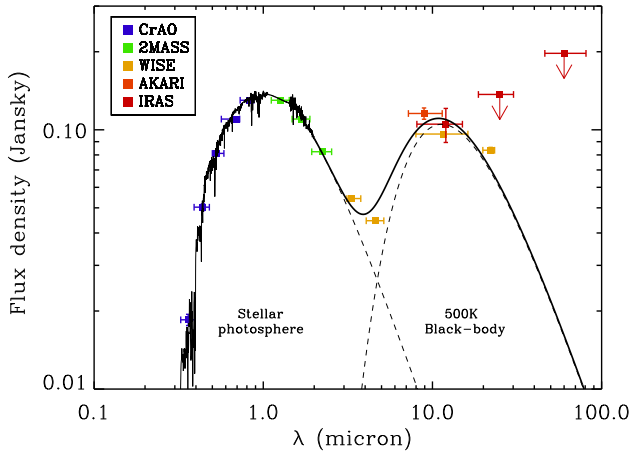


Fig. 1. The SED of RZ Psc. A K0IV model photosphere (Pickles 1998) fits the optical and near-IR measurements shortward of $3 \mu\text{m}$. Longward of $3 \mu\text{m}$, the excess emission is markedly dominant and contributes 8% to the total source luminosity. The solid black line corresponds to the total flux of stellar photosphere plus a single black-body curve of 500 K. Some uncertainties in flux measurements are smaller than the used plot-symbol. The errorbars in wavelength indicate the width of the filter corresponding to 50% transmission.

$b = 0^\circ$. Clearly this is an uncertain exercise, but the result is consistent with the observed Li equivalent width, which is consistent with an age between 10 and 70 Myr. Recently, we measured a v_{rad} of $-2.0 \pm 1.5 \text{ km s}^{-1}$ (Potravnov & Grinin 2013), consistent with the ones reported in Shevchenko et al. (1993), but in disagreement with the literature value (-11.5 km s^{-1}) used in Paper I. Using the new value, the kinematic age changes slightly to $t_{\text{kin}} \sim 25 \pm 5 \text{ Myr}$ (standard error). Arguments in support of a system older than 10 Myr include the absence of interstellar dust extinction towards RZ Psc (the star lies far from active star formation regions) and the lack of $H\alpha$ emission. In the following, we will discuss the star's properties assuming that the star has finished its formation process, because the age constraints available exceed the characteristic time for optically thick accretion disks found for classical T Tauri stars, but keeping in mind that the system is nonetheless relatively young.

3.1. The Spectral Energy Distribution

The resulting spectral energy distribution (SED) is presented in Fig. 1. It reveals the star's photospheric emission at visual wavelengths and strong excess emission dominating the total radiation from $3 \mu\text{m}$ onwards. We note that the photospheric fit does not require an extinction correction (Kaminskii et al. 2000). IR excess emission is observed among a small fraction of main-sequence stars, *viz.* the debris disk objects (Wyatt 2008). The emission is caused by warm dust particles released in collisions between planetesimals in belts similar to the asteroid and Kuiper belt of our Solar System (Wyatt 2008). However, the excess emission observed in RZ Psc is found to have two outstanding properties that sets it apart from regular debris disk systems.

1. The dust emission is well approximated by a single 500 K Planck function, strongly constrained by the WISE $22 \mu\text{m}$ measurement. The temperature of the warm dust is far lower than the dust sublimation temperature of approximately 1500 K. This implies that (1) orbits closer to the star are (practically) devoid of dust grains otherwise dust excess emission would be detected in the $2 \mu\text{m}$ wavelength region; and (2) that the dust distribution

is limited in radial extent (a ring rather). Assuming heating by stellar irradiation and dust particles in thermal equilibrium with an optically thick environment one can estimate the radial distance of the dust by applying $T_d \approx T_{\text{eff}}(r/r_*)^{-1/2}$. Adopting the stellar parameters $T_{\text{eff}} = 5250 \text{ K}$ and $R_* = 1.5 R_\odot$ (Paper I) delivers a characteristic distance for the dust of 0.7 AU. Dropping the optically thick assumption and assuming optically thin dust instead, this characteristic distance reduces to 0.4 AU. In addition, any cold (100 K) dust component cannot be excluded by the current set of measurements, but the total emission at $60 \mu\text{m}$ should be $\lesssim 0.05 \text{ Jy}$.

2. The second unusual property is the high fractional contribution of the excess to the total luminosity which amounts to 8%; this excess places the star among the non-accreting objects with the strongest IR excesses¹. We can estimate the expected fractional contribution by the production of small dust particles in a model for a steady-state, collisional cascade of an asteroid belt, thought to be valid for debris disks (Wyatt et al. 2007a). In brief, a steady state model adopts a planetesimal size distribution that does not evolve, except that the largest-sized bodies disappear by collisions and the minimum size is set by stellar radiation pressure effects. The cascade model predicts a maximum infrared belt luminosity with time (eq. 18 in Wyatt 2008). If the evolution of the planetesimal belt of RZ Psc is similar to that observed in A-type star debris disks (for which a fitting steady-state representation is parametrized by a maximum asteroid size of 60 km, planetesimal strength of 150 J/kg and eccentricity of 0.05) then with a characteristic distance of 0.7 AU a belt width of 0.3 AU, a fractional luminosity contribution of a few times 10^{-5} is predicted at the adopted age of RZ Psc. This is a common value for debris disks. Much more mass in small dust grains needs to be produced in RZ Psc than can be accounted for by the steady-state collisional paradigm. We can use equation (4) from Wyatt (2008) to convert the 8% fractional contribution to a lower limit on the mass, *viz.* $M_{\text{disk}} > 1 \cdot 10^{23} \text{ g}$. This conversion assumes that the fractional luminosity defines the effective cross-sectional area of the dust, *i.e.* an optically thin environment (dust edge at 0.4 AU). Additionally, we adopt a single size and density for the dust particles, $10 \mu\text{m}$ and 3.3 g cm^{-3} respectively (following Lawler & Gladman 2012). However, if the same dust is responsible for the excess emission *and* the UXOR variability, then clearly the size of the dust should be (sub-)micron sized.

A dust belt with a sharp inner edge can be produced by dynamical interactions between the dust and a secondary object located within the gap between star and belt (Williams & Cieza 2011; Kraus & Ireland 2012). If we assume this to be the case in RZ Psc, then we can derive the following about the secondary's properties. For a zero eccentricity orbit, the semi-major axis of the secondary has to be approximately half that of the inner edge of the belt, (semi-major axis between 0.2 and 0.4 AU) (Artymowicz & Lubow 1994). The absence of any radial velocity variation down to 2 km s^{-1} (Shevchenko et al. 1993), results in a secondary mass of $\lesssim 38 M_{\text{Jup}}$ for optically thin dust (or $\lesssim 53 M_{\text{Jup}}$ for the optically thick case). For a non-zero eccentricity orbit of a secondary object sculpting the inner rim of the dust distribution, the semi-major axis could be even smaller (e.g. Beust 2003) and the mass upper limits are then also correspondingly lower.

Alternative processes for explaining an inner-gap by means of grain growth (as the first step in the planet formation process) or photo-evaporation (responsible for the dissipation of the

¹ A contribution $>16\%$ was recently reported for the 60 Myr solar-type star V488 Per (Zuckerman et al. 2012).

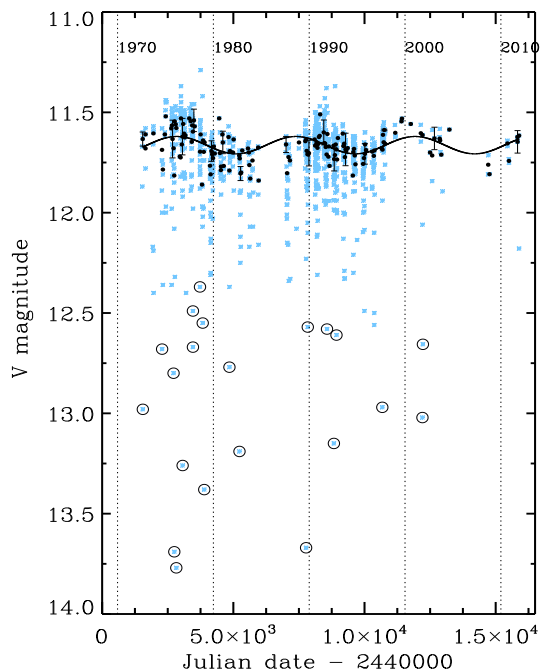


Fig. 2. The light curve of RZ Psc stretching 40 years. Over one thousand measurements are plotted (small blue stars). Gaps in the measurement coverage are caused by seasonal observability of the object on the sky. The deepest minima ($\Delta V > 1$) are marked with open circles. Additionally, the flux at bright phases varies periodically. This periodicity is revealed by sigma-clipping and time-binning the data resulting in the points represented by black circles whose 12.44 year period is marked by the sinusoid (see text). Typical uncertainties in the clipped-binned data are indicated only in 10% of the plotted points.

primordial accretion disk, especially the disk's outer-parts) are unlikely because they play a role in optically thick primordial disks during the first 10 Myr of the evolution (Cieza 2008).

3.2. The optical variability

A large mass in small dust particles provides a reservoir for the dust occultation events depicted in Fig. 2. The figure shows the photometric activity of the star over the past forty years. The light curve is based on our own observations and the data from literature (Zaitseva 1985; Kardopolo, Sakhanenok & Shutevova 1980; Pugach 1981; Kiselev et al. (1991); Shakhovskoi et al. (2003)). Two phenomena can be identified:

(1) Brightness decreases of up to 2.5 visual magnitudes. They occur on average once every year but the events are aperiodic. The brightness minima last 1 to 2 days. From the rate of flux change, one can estimate the tangential velocity and approximate the distance for an opaque screen (Paper I). From this, an orbital distance of 0.6 AU is found, not inconsistent with the distance estimated from the excess emission. The flux minima are accompanied by an increased degree of polarization (Kiselev et al. 1991; Shakhovskoi et al. 2003), which, taken together, unambiguously identify small, micron-sized, dust grains as the cause (Grinin et al. 1991). The occultation time then limits the characteristic size for the clumps to ~ 0.05 AU. The extinction at the beginning of the eclipses displayed by RZ Psc is typical for UX Ori stars, and these can be described approximately by assuming MRN size distribution for sub-micron sized particles (Voshchinnikov et al. 1995). Adopting the opacity at optical wavelengths

for an ISM dust mixture (Natta & Whitney 2000), and with the observed $\tau_v = 3$ of the dust clump (not an uncommon value for UXORs), we derive a mass of a few times 10^{20} g (assuming the clump consists of dust only).

(2) A modulation of the peak flux with a cycle of 12.4 years. The brightness variability of RZ Psc has been presented in previous publications reporting a quasi-periodic variation of the stellar flux level during bright periods albeit with different periods (Shakhovskoi et al. 2003; Rostopchina et al. 1999). Here we present a rigorous analytical period-search with the aim to settle the question of any periodicity in RZ Psc's photometric data of the past forty years.

The light curve data present two challenges for period searches. First, the data sampling is unevenly spaced in time both due to seasonal observability and weather conditions. Second, the brightness variability is dominated by an intrinsically irregular component dominating the variability on a time-scale of days, i.e. the obscuration of the star by the dust clumps. The amplitude of the irregular variation is larger than the measurement precision of less than approximately 0.03 magnitudes. We performed a period search on a subset of the data, which was defined by discarding measurements deviating more than 2σ from the median brightness of the source. This step aims to remove the signal caused by the obscuration events that lead to the deep brightness minima. In the next step, the data were averaged per time-bin with the aim to average out the small amplitude of $\sim 0.3^m$ daily variability of the source. An optimal bin-size of 29 days was objectively calculated according to a method which minimizes the bin-size by taking into account the bin statistics (mean and variance) of the finite sample (Shimazaki & Shinomoto 2007). The bin-averaged data points are represented in Fig. 2 by blue symbols and the errorbars represent the uncertainties taken to be the standard deviation per bin. If a time-bin contains only one measurement then the average time-bin standard deviation is assigned. Finally, a period search was performed by computing the Generalized Lomb-Scargle (GLS) periodogram (Zechmeister & Kürster 2009). This methodology revealed a significant power at a period of 12.34 years with a false alarm probability of $6.8 \cdot 10^{-4}$. No other significant power peaks are present in the GLS periodogram. A subsequent sinusoidal fit delivers a refined period of 12.44 years an amplitude of 0.5 magnitude which is presented in Fig. 2. Removal of this periodic signal from the data results in a power-spectrum without significant power beyond the noise.

The cyclic variability of cool stars can be connected with the magnetic surface activity (magnetic cycles, see, e.g. Grankin et al. 2008). This type of activity is frequently accompanied with the rotational brightness modulation of stars not viewed pole-on (e.g. Vrba et al. 1988). RZ Psc is observed close to equator-on and its brightness does not display any rotation modulation. The cause for the long-term cyclic variability of RZ Psc could be because of a warped disk (Grinin et al. 2010) or large-scale perturbations in a disk, as is suggested for UXORs (Grinin et al. 1998). Such perturbations can be caused by the orbital motion of a co-planar low-mass companion (Demidova et al. 2010). We speculate here, that if this is so then the system is required to have a second low-mass companion. Taking into account a 30% uncertainty in star mass and 0.25 year on the period, the semi-major axis of this tertiary component is $a = 5.3 \pm 0.6$ AU. We note that the application of this particular model to RZ Psc is possible only if the outer part of the disk (beyond the orbit of the second companion) contains some amount of gas and fine dust. This material could be the remnant of the primordial disk. This scenario would predict the existence of a far infrared excess with

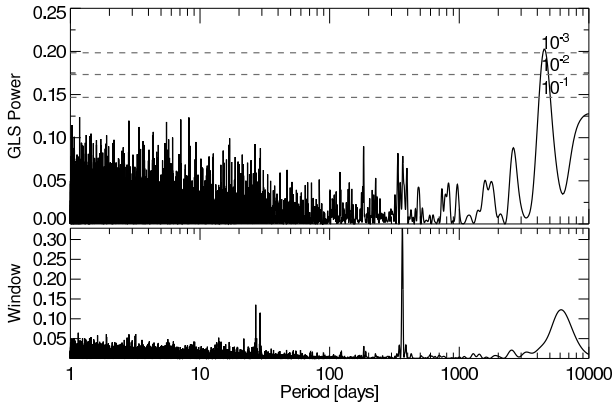


Fig. 3. Generalized Lomb-Scargle periodogram and window function. The computed periodogram (upper plot) is a convolution of the astrophysical signal present in the data and the sampling function present in these data (window function, lower plot). The periodogram is obtained from the sigma-clipped, bin-averaged dataset. The horizontal dashed lines indicate FAP levels of 10^{-1} , 10^{-2} , and 10^{-3} . There is one significant peak present at a period of 12.34 years with a FAP of $6.8 \cdot 10^{-4}$. The window function shows a significant peak at 365 days which is caused by the seasonal visibility of the source. However, significant alias peaks caused by the sampling period are not present in the GLS periodogram.

$T \leq 100$ K. We underline that for a full understanding of the RZ Psc system in particular the effects on the dust distribution by the two inferred companion objects, numerical modeling is required.

3.3. Warm debris disks

RZ Psc adds to a growing number of main-sequence stars with exceptionally strong, warm (500 K) infrared excess. The excesses are orders of magnitude stronger than can be explained by the collisional cascade model applicable to regular debris disks (Song et al. 2005; Melis et al. 2010; Zuckerman et al. 2012; Lawler & Gladman 2012). Evidence is mounting that the warm debris disks are generated by transient, or stochastic events based on the observed altered emission properties of the dust grains (Olofsson et al. 2012). Proposed transient events constitute a recent collision between two major bodies (like rocky planetary embryos or even planets, Melis et al. 2010) or a second planetesimal belt at larger radii feeding the inner dust distribution with evaporating comets and/or inducing collisions, partially analogous to the Solar system Kuiper belt (Olofsson et al. 2012). Involved time-scales would favour the former explanation supported by the fact that warm dust phenomenon near solar-type stars may occur only in the first 30 to 100 Myr as judged from a sample of four field stars (Melis et al. 2010). Also young stellar clusters indicate a maximum in the number stars that show $24 \mu\text{m}$ excess emission around approximately 40 Myr (Smith et al. 2011). RZ Psc is unique in the sense that the system's near equator-on orientation and dust occultations give important clues to the dynamics of the system.

4. Conclusions

We have detected a strong mid-IR excess in the young star RZ Psc with an 8% fractional contribution to the bolometric luminosity of the system. The excess traces warm dust and it is well described by a single Planck function of ~ 500 K. It suggests a radially compact dust distribution (a ring), with the inner-edge at 0.7 AU if the dust is optically thick. We also find a peri-

odicity of 12.4 years in the maximum optical brightness of the object. Although uncertain, the estimates for the age indicate that the star is beyond a formative phase and the mid-IR excess is unlikely to be caused by a primordial disk. Therefore, copious amounts of small dust need to be continually produced in this system to explain the optical occultation events (UXOR phenomenon), providing a dynamical view on the dust production process. The RZ Psc system could play a key-role in understanding the transition from primordial disks to debris disks.

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